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"The Mark III Linac As a High Current Source For FEL Experiments"

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Principal Investigator: Professor Mason R. Yearian
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The Mark III single section tests have been generally successful. In particular, it has been observed that the Mark III accelerator sections are capable of operating reliably and stably at high gradient if an appropriate vacuum is maintained in the structure, and if appropriate steps are taken to bake out the adsorbed contamination on the cavity walls. Electrons have also been accelerated in the test section to an energy in excess of 40 MeV.

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Introduction

The basic objective of this research was to determine the feasibility of the conversion of the Stanford Mark III linac to high-gradient operation to serve as an injector or driver for storage ring and single pass free electron laser experiments. See #1473 Specifically, we proposed to:

(1) restore to operation a single section of the old Mark III linac, replacing the 15 megawatt pulsed klystrons originally used in the linac with a 30 megawatt SLAC tube, and whatever additional equipment might be required for high-gradient operation.

(2) Determine the breakdown characteristics of the Mark III accelerator structures when driven at high power using the new klystron.

(3) Determine the maximum attainable energy gradient when using the new klystron.

As secondary goals, we planned to evaluate the performance of the new modulator and klystron with respect to phase and amplitude stability reliability, RFI and EMI to determine the suitability of the components for use in our proposed general upgrade of the Mark III. The single section tests would also give us the opportunity to develop and test the vacuum system and the low level instrumentation and control systems proposed for the upgrade.

As described further below, the Mark III single section tests have been generally successful. In particular, we have observed that the Mark III accelerator sections are capable of operating

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reliably and stably at high gradient if an appropriate vacuum is maintained in the structure, and if appropriate steps are taken to bake out the adsorbed contamination on the cavity walls. Electrons have also been accelerated in the test section to an energy in excess of 40 MeV.

Experience gained in these tests is being applied in the development of plans to upgrade the remainder of the MK III as part of the Air Force supported Linac/Storage Ring FEL facility. The test section will be available for use in its present form as a driver for single pass FEL experiments during the construction of the Linac/Storage Ring Facility.

II. DESCRIPTION OF EXISTING MARK III HARDWARE

Regularly scheduled operation of the MK III ceased in 1969, though the machine continued to be run sporadically for special projects until 1975. At the start of our research, the machine was basically in mothballs, with all power shut down, and all vacuum systems let up to air or filled with nitrogen gas. The major features of the existing hardware are described below.

The Accelerator Sections: The MK III was equipped with 31 SLAC-type iris-loaded travelling wave accelerator sections. The sections were designed to operate with a $2\pi/3$ phase shift per cell, and to provide a constant accelerating gradient. The structures' nominal operating frequency is 2.856 Gigahertz (see Figure 1).

The nominal energy gain of the sections can be computed from the equation:[1]

$$V = (1 - e^{-2\tau})^{\frac{1}{2}} \quad (P\ell r)^{\frac{1}{2}}$$

$$- \frac{Ir\ell}{2}\left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}}\right)$$

where $V \equiv$ net electron energy gain (electron volts)

$\tau \equiv$ net attenuation along sections (nepers)

$= \frac{wt_f}{2Q} = .57$ Neper for SLAC sections

$r \equiv$ shunt impedance

$=$ 53 megohms/meter for SLAC sections

$\ell \equiv$ overall section length (meters)

$=$ 3.05 meters for SLAC sections

$P \equiv$ input power in watts

$I \equiv$ averge electron beam current during pulse. (amperes)

Neglecting beam loading, the net energy gain for a 10' SLAC section is $V(\text{in MeV}) = 10.5 \sqrt{P(\text{in megawatts})}$.

The maximum energy obtained from the 31 sections of the old MK III was 1.1 GeV with no beam loading.[2] Electron currents as high as 13 mA were obtained; at this current the energy gain per section was reduced by beam loading by 0.5 MeV.

To attain 1.1 GeV the average energy gain per section in the old MK III was 38.7 MeV, corresponding to an rf power input of 14.5 megawatts per section. The nominal RF pulse length for the MK III was 2.0 microseconds, and the repetition rate was 60 hertz.

Although the SLAC linac uses higher power klystrons than were available when the MK III was built, the actual RF power input per section was smaller since the output of each klystron at SLAC is divided four ways to drive four linac sections. At a net klystron power output of 30 megawatts, the power per section at SLAC is thus only 7.5 megawatts. Use of the "SLED" energy storage cavities at SLAC permit this power to be doubled to 15 megawatts, at reduced pulse length.

In our proposed tests of the MK III the klystron power input per section would be raised to 30 megawatts at a pulse length of 3.5 microseconds, a higher power input and longer pulse length than had been used either at the old MK III or at SLAC. Since the probability of an RF breakdown of a cavity increases with both the peak RF power and the pulse length,[3] these proposed operating conditions represented a significant advance in performance for the accelerator structure. As described further below, additional

questions were raised by the contamination of the accelerator structures by small quantities of vacuum pump oil, which has generally been observed to lower the breakdown threshold.

The Vacuum System: The MK III accelerator sections and waveguide were evacuated by untrapped oil diffusion pumps using mechanical forepumps. Backstreaming oil from the diffusion pumps and mechanical pump oil from the fore-pumps had contaminated all the cavities to some degree. The base pressure attained by the old vacuum system was 1×10^{-6} Torr.

The vacuum system for the accelerator section tested in this program had to be completely rebuilt to eliminate the backstreaming oil problem and reduce the base pressure. The principal issue for the new vacuum system was the extent to which the oil contamination on the walls of the accelerator sections could be removed by bakeout. If high temperature bakeout was not effective, the structure would have to be chemically cleaned, a much more time-consuming and expensive process.

The RF Drive System: Drive to the accelerator sections of the old MK III was provided by a relatively low-gain (30 dB) pulsed klystron with a nominal power output of 15 megawatts. Though revolutionary in their time, the gain and power output of the MK III klystrons were insufficient for high gradient operation. The drive system for the klystrons was also inadequate for the proposed research, consisting of a crystal oscillator-frequency multiplier chain followed by a pulsed klystron amplifier chain

which delivered, ultimately, 10 megawatts peak power to be divided among the 31 klystron power amplifiers which actually drove the MK III.

While less power would be required to drive the 30 megawatt SLAC klystrons proposed for use in our tests, it was thought desirable to provide a more stable and flexible master oscillator than the old crystal oscillator system, and to provide improved diagnostics for the forward and reflected high power RF delivered by the new klystrons to the accelerator test section.

Modulator: Sixteen of the 31 modulators used in the old MK III used 110 kilovolt pulse forming networks switched by triggered spark gaps. The remaining fifteen modulators, which had been modernized in the early 1960's,used 37 kilovolt pulse forming networks switched by hydrogen thyratrons. The repetition rate for all the modulators was 60 Hz, and the pulse length 2.5 microseconds.

Although much experience had been accumulated at SLAC during the operation of their 65 megawatt modulators,[5] the repetition rate and pulse lengths requirements for the FEL experiments planned for the reconditioned MK III differed significantly from the SLAC parameters. These differences required both a new PFN design, and a differing choice of PFN components than were used at SLAC. In addition, it seemed desirable to carefully review the configuration of the high power storage and switching elements

in the new modulators to minimize the RFI and EMI generated during operation.

Electron Gun: The three-element electron gun originally used with the MK III was available for use in the single-section tests. Designed to operate at 80 kilovolts with a pulsed extractor and first anode, the gun was capable of producing peak currents of the order of 1 ampere at a micro perveance of .5.

As originally used in the MK III the gun was followed by an S-band pre-buncher cavity and a pair of focussing lenses to match the electron beam into the accelerator structure. Although a new gun would clearly have to be developed to support the FEL experiments proposed for the MK III, and some improvements in focussing optics, diagnostics, and vacuum were necessary, the existing gun was basically adequate as an electron source for the measurements of energy gain in the single section tests.

Temperature Control: Cooling water for the MKIII had been supplied by three 8 million BTU/hour cooling towers. These cooling towers had not been used since 1975, and were generally inoperable at the start of our tests. However, for the purpose of our tests, adequate cooling water could be obtained by bypassing the cooling towers and simply circulating water from the laboratory's cooling water sump. Though adequate for low power tests, major rework of the cooling water system will be required when the remainder of the MK III is returned to operation.

Shielding: Substantial steel and concrete shielding had been installed around the MK III to provide personnel protection during its operation at 1.1 GeV. No additional shielding was required for our single section tests, which would not exceed 60 MeV (see Figure 3).

Radiation Monitoring: The radiation monitoring system of the old MK III was not functioning at the time we began this research and, in any event, would not have satisfied present health physics standards.

Electron Spectrometer: A 30° magnetic electron spectrometer was available in the old beam switchyard for use in the single section tests. The spectrometer was instrumented with a series of fluourescent screens, a variable entrance aperture, and a series of thin-foil fingers to measure the electron distribution at the output of the spectrometer, though the electronics for the latter were inoperative at the time we began the tests (see Fig. 2).

The principal issue for the spectrometer was its calibration. The spectrometer had been calibrated for use in the 100 MeV - 1.0 GeV range,[6] and had not previously been used in the 50 MeV range. Hysteresis effects were also a more serious problem at these low energies than above 100 MeV.

III. MODIFICATIONS AND NEW EQUIPMENT INSTALLED FOR HIGH GRADIENT TESTS

Vacuum System: We developed a new oil-free vacuum system with ion pumping for the accelerator section under test and the beamline to the 30° spectrometer in the bunker. The buna-N O-rings and lead gaskets previously used to form the vacuum seals were replaced by conflat flanges using copper gaskets. The base pressure in the accelerator sectio with the new vacuum system was 5×10^{-8} torr.

For the initial tests of the vacuum system and the l-erator sections we monitored the residual gas composition using a quadrupole mass analyzer borrowed from SLAC.

Note also that we had to remove the accelerator sections following the section under test to prevent the deceleration and broadening of the electrons by the non-operating sections. The removed sections were replaced by 4" stainless and aluminum pipes.

RF Drive System: We developed a new RF drive system using a Marconi 2019 frequency synthesizer as a master oscillator, a solid state frequency tripler, a TWT amplifier, and the low power SAS61 pulsed klystron used as a pre-amplifier in the old MK III system. Drive power to the 30 megawatt pulsed klystron in the new system is controlled by an attenuator and phase-shifter following the SAS61. A 30 megawatt RCA klystron, borrowed from SLAC, is used to drive the accelerator section under test (see Figures 4,5 and 6).

To monitor the output power of the 30 megawatt klystron and the power reflected from the accelerator cavity, we had to develop a high power, high-isolation directional coupler for the evacuated waveguide used to carry the RF power from the klystron to the accelerator. Using the Moreno geometry and a controlled mismatch at one port of the coupler we achieved an isolation of 50 dB at a coupling of 40 dB.

Modulators: A new pulse forming network and thyratron switching circuits was developed to drive the new 30 megawatt klystron. The pulse forming network was designed to provide a 3.5μsec pulse length with an 800 nanosecond risetime. The new charging system, incorporating the dc power supply and charging inductor from the old modulators, was capable of charging the PFN at voltages up to 45 KeV at a repetition rate of 30 Hz (see Figure 7).

As part of the development of the new modulators, we also developed new instrumentation and control systems for the modulators including controls for the DC power supply voltage, a current monitoring system for the power supply and modulator, and a new safety interlock system.

The pulse power components - the PFN and thyratron switching circuits, was mounted in a continuous aluminum enclosure bonded to the outer conductor of the triax line feeding the klystron to minimize generation of voltage and current transients in the low power circuits of the linac.

Electron Gun: The seals and pumps of the old MK III gun were upgraded to provide a vacuum compatible with the base pressure of the test section, and the gun modulator was rebuilt to provide a broader range of gun voltage and currents than attainable in the old modulator. A series of Helmholtz coils was installed around the gun and the first cells of the linac to provide increased flexibility in the transport of the electron beam from the gun to the linac (see Figure 8).

Timing Circuits: To synchronize the klystron and gun modulators, we developed a digital delay triggering system. The delay system both generates the firing signals for the gun and klystron modulators and permits the start of these trigger signals, to be delayed digitally in steps of 400 nanoseconds with continuous analog interpolation. Though controlled manually in these tests, the timing system is designed to be interfaced with a central control computer (see Figure 9).

The timing circuits are required to compensate for the inevitable spread in thyratron delay times for the two systems. The timing circuits were designed as prototypes for the circuits required in the general MK III upgrade.

Diagnostics: To assist in the set-up of the linac and the characterization of the electron beam we have installed a number of new diagnostics before and after the linac test section in-

cluding fluorescent screens, toroid current monitors, and high level radiation monitors. An energy resolving foil beam position monitor was also added at the output of the 30° magnetic spectrometer in the bunker (see Figure 8).

Personnel Protection System: To satisfy current health physics regulations, we developed 12 low-level ionization chambers for placement in the laboratory outside the radiation shielding of the test sections. The ionization chambers provided a sensitivity of 5 milliroentgens full scale, and were designed to facilitate multiple radiation level readouts and a simplified computer interface. A series of emergency beam cut-off switches and interlocks were also added around the perimeter of the shielding for the test section (see Figure 10).

IV. RESULTS

RF Breakdown Characteristics: We have tested two accelerator sections employing low and high temperature vacuum processing protocols. The system baked out at low temperatures did not withstand RF power inputs greater than 15 megawatts. The section baked out at high temperature has operated at the highest power level available from the new SLAC klystron.

The two sections which were tested had lengths, respectively, of 8' and 10.' Note that for RF purposes, the eight foot

section used in the tests is identical to the 10' section. The size of the input coupler and the individual cavities and coupling irises is the same in both structures, except for the last 23 cavities which were omitted in the 8' section. Both sections were initially baked under vacuum at a temperature of 100^{o} C for three weeks. This bakeout was sufficient to reduce the hydrocarbon components of the residual gas measured by the quadrupole mass analyzer to a low level. This bakeout was initially thought adequate to remove the adsorbed vacuum pump oil from the cavity walls (see Figure 11).

We attempted to process the 8' section to high power immediately following the 100^{o}C bakeout. We started the processing at low power, typically a few hundred kilowatts, and gradually proceeded to higher power while watching the system's vacuum gauges and the RF diagnostics for signs of breakdown. Monitoring the reflected power, we observed that breakdown always started at the trailing edge of the pulse, and gradually walked to the front edge of the pulse. The extent and approximate location of the breakdown could be estimated from the relative vacuum pressures at the two ends of the structure under test. For the 8' section, the relative pressures indicated a location very near the input coupler to the sections. This was confirmed by visual inspection of the first cavity of the structure, which was deeply pitted by the arcs which developed under breakdown conditions.

Although the threshold for breakdown of the 8' section could initially be raised by continued operation at a RF power level or pulse length just below the threshold, the section would not process up beyond about 15 megawatts. In fact, continued operation at this power level resulted in the general deterioration of characteristics; the experiment was eventually halted by the failure of the klystron output window at the vacuum pressure encountered under breakdown conditions during the test.

In contrast to the 8' section, the 10' section was processed comparatively rapidly to the 30 megawatt level. We attribute this improved performance to a second, high-temperature bakeout which was used with the 10' section. Before injecting RF, we baked the 10' section for several days at 400° C under high vacuum, yielding an ultimate base pressure of 5×10^{-8} torr. We then processed the section with RF, and after a few hours, could operate the section at the full 30 megawatt klystron output power for a 3.0 microsecond RF pulse length.

Following the initial processing to 30 megawatts, the 10' section could be reprocessed to this level from cold start in less than a minute with a negligible rise in pressure during processing. To test its long-term operating characteristics, the 10' section has been run at least once every week since its first operation, accumulates a total running time of approximately 50 hours. The typical breakdown rate during these tests was less than one event per hour (see Figure 12).

Our experience with the 10' section compares very favorably with SLAC's experience. Though the maximum power input to the SLAC sections is only 7.5 megawatts (un-SLEDded), and the pulse lengths only 2.5 microseconds, SLAC always observes significant gas evolution when processing their cavities up to full power from shut-down conditions. We attribute the improved performance we have observed to the improved base pressure and pumping spread in the MK III test section.

Energy Gradient: The theoretical gradient at 30 megawatts RF power input computed using equation 1 is 18.9 MeV per meter, yielding a net energy gain of 57.5 MeV for the 10' section. The measured energy gain using the 30° iron spectrometer was 45 MeV, 12 MeV below the theoretical value. At this time, it is uncertain that the discrepancy is real since the spectrometer was calibrated for use at higher energies (see Figure 13).

Modulator Characteristics: The new modulator constructed for the single section tests has been operated at power outputs as large as 113 megawatts, 28 megawatts higher than the 85 megawatts required to drive the 30 megawatt SLAC klystron. The measured ripple during the 3 microsecond pulse was $\pm$ 0.4%, corresponding to a $\pm 3^{\circ}$ phase jitter at the klystron output (see Figs. 14 and 15).

No problems were encountered with the modulator when driving the SLAC klystron beyond the failure of a silicon end-of-line diode used to limit the voltage excursion of the PFN under klystron

fault conditions. We are attempting to locate a source for diodes with a higher surge current to eliminate this failure mode.

Low Power RF System: In general, the low level RF system has operated satisfactorily except for the SAS61 pulsed klystron amplifier which has operated at lower than specified gain, and has been somewhat noisy. The SAS61 is no longer manufactured, and will in any event have to be replaced in the future.

Waveguide: Our experience in the construction and operation of the evacuated waveguide feed system for the MK III test section has convinced us that pressurized waveguide should be used in the upgrade of the remainder of the linac. Use of pressurized waveguide will reduce material cost and simplify fabrication by permitting the use of standard thin-wall brass or aluminum waveguide. Pressurized waveguide will also improve klystron window lifetime, reduce barometric effects, and permit klystron maintenance or exchange without loss of vacuum in the linac.

General Instrumentation: All low level controls and instrumentation have functioned as designed.

V. FUTURE PLANS

To secure a more favorable current and pulse length for the FEL experiments proposed for the first section of the reconditioned Mark III, we plan to develop a low emittance microwave driven gun using a lanthanum hexaboride cathode and to extend the klystron pulse length from 3.0 nsec to 10.0 μsec.

VI. SUMMARY

We conclude from these tests that the MK III accelerator sections can be used with RF power inputs as large as 30 megawatts provided that adequate oil-free pumping is provided during operation, and that the sections are baked out under vacuum prior to operation.

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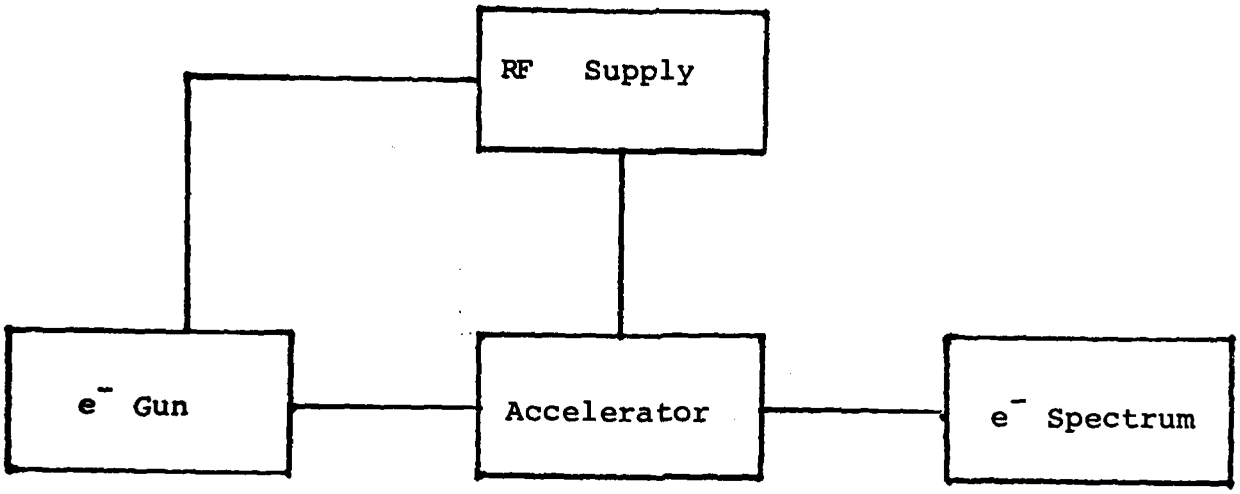


Accelerator Test Section

Block Diagram

FIGURE CAPTIONS

Figure 1: Typical constant gradient s-band accelerator structure. The accelerator sections were brazed in 8' and 10' lengths at SLAC from a series of copper plates and cylinders. The tubes running along the length of the section carry the cooling water to regulate the temperature of the structures. The sections tapered waveguide load is visible attached to the end of the structure.

Figure 2: The 30^{o} magnetic spectrometer (foreground) used to measure the net energy gain and energy spectrum of the test section.

Figure 3: Concrete block shielding wall enclosing the test section.

Figure 4: Low-power RF drive system. The 952 MHz output of the synthesizer was tripled to obtain 100 microwatts of power at 2856 MHz. This signal was amplified by a cw TWT to the 1 watt level, and further amplified to the kilowatt level by a pulsed SAS G1 klystron to drive the SLAC 30 megawatt klystron.

Figure 5: SLAC 30 megawatt klystron. The oil-filled tank enclosing the cathode step-up transformer is visible at the base of the tube. The barrel-shaped Alnico focussing magnet is visible at the tube's mid-section.

Figure 6: Block diagram showing the principal electrical and RF components of the MK III test-section set up.

Figure 7: 85 megawatt modulators for the SLAC klystron. The LC pulse-forming network is visible at the mid-section of the aluminum enclosure. The hydrogen thyratron switch tube is visible at the bottom of the enclosure.

Figure 8: Electron gun for the MK III test section. The glass envelope of the gun is visible in the foreground, followed by the s-band pre-buncher cavity and the gun's electron optics.

Figure 9: Control panel for the MK III test sections. The power supplies in the center and right hand racks control the focussing and steering magnets used to transport the electron beam to the 30° spectrometer. The timing generator is visible in the left-hand rack.

Figure 10: Low-level ionization chamber used to monitor radiation levels outside the concrete shielding enclosing the test section.

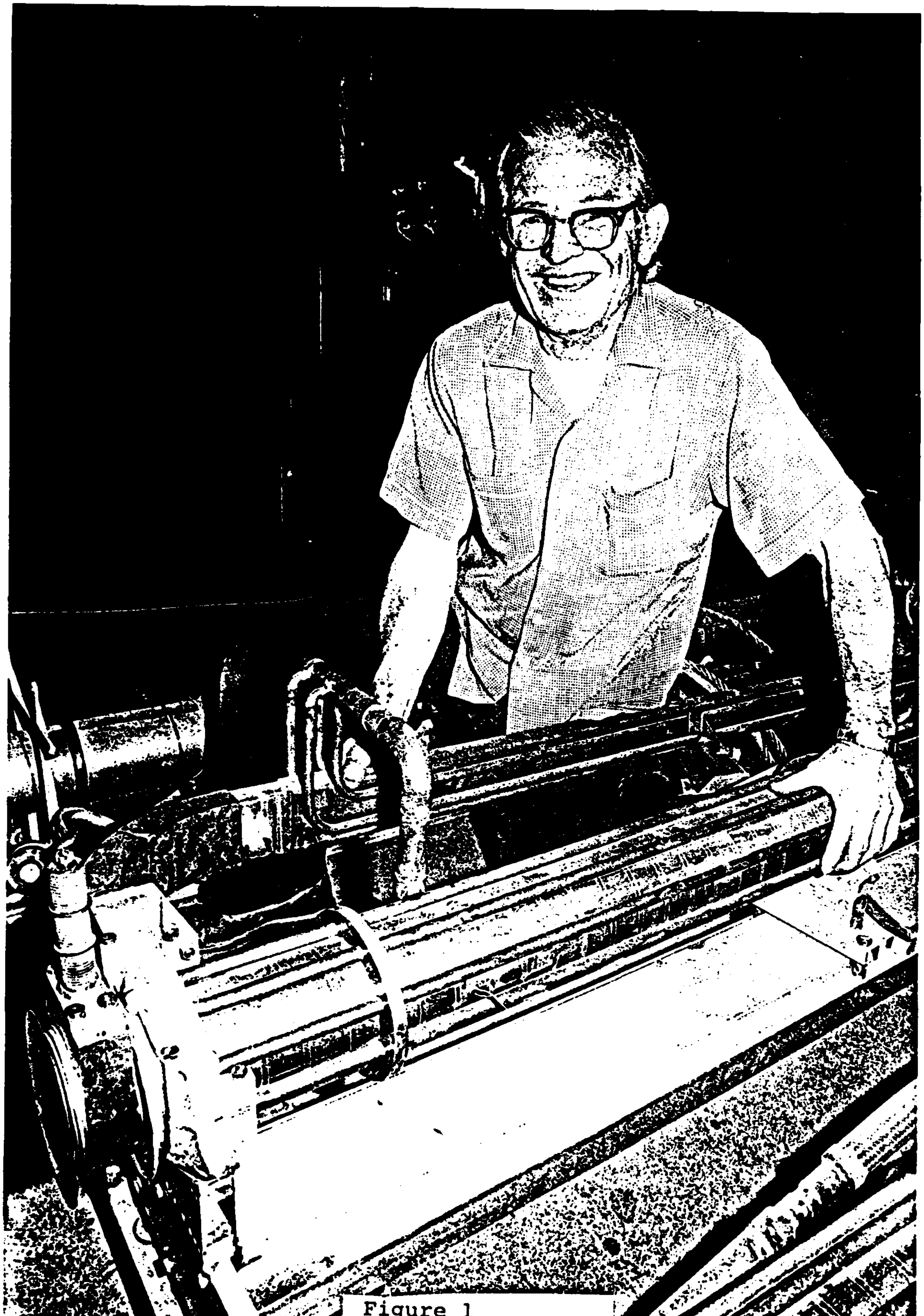
Figure 11: Residual gas pressure in the 8' test sections after the 100° C bakeout. The hydrocarbon peak in this seen is below 2×10^{-8} torr.

Figure 12: Tracing of vacuum pressure in the 10' test section during the application of RF power following a week's shut-down. The tracing starts at zero RF power input and reaches 30 megawatts after 2 minutes. The maximum pressure observed during turn-on is typically 10^{-6} torr.

Figure 13: Energy sprectrum produced by the 10' test section as recorded on the multiple-foil beam position readout at the output of the 30° spectrometer.

Figure 14: Envelope of RF pulse produced by the 30 megawatt SLAC klystron.

Figure 15: Measured phase shift of the SLAC 30 megawatt klystron in the MK III tests. The linear phase shift in the photo, equivalent to a frequency shift, is due to the droop of the klystron's cathode ste-up transformer. The periodic oscillations in phase ($\pm 4^{\circ}$ peak) is due to the ripple in the pulse generated by the modulator's lumped-constant pulse forming network.



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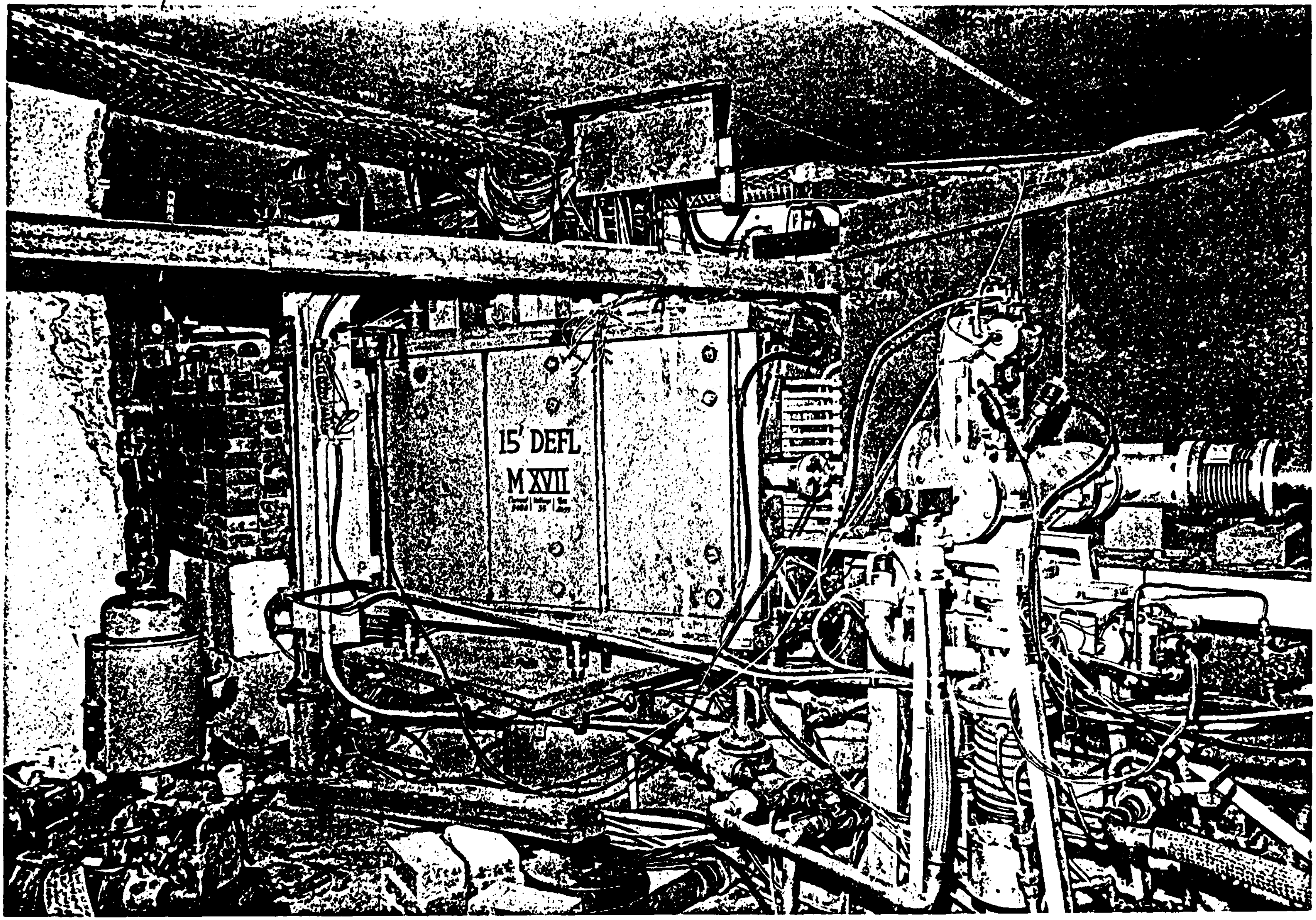

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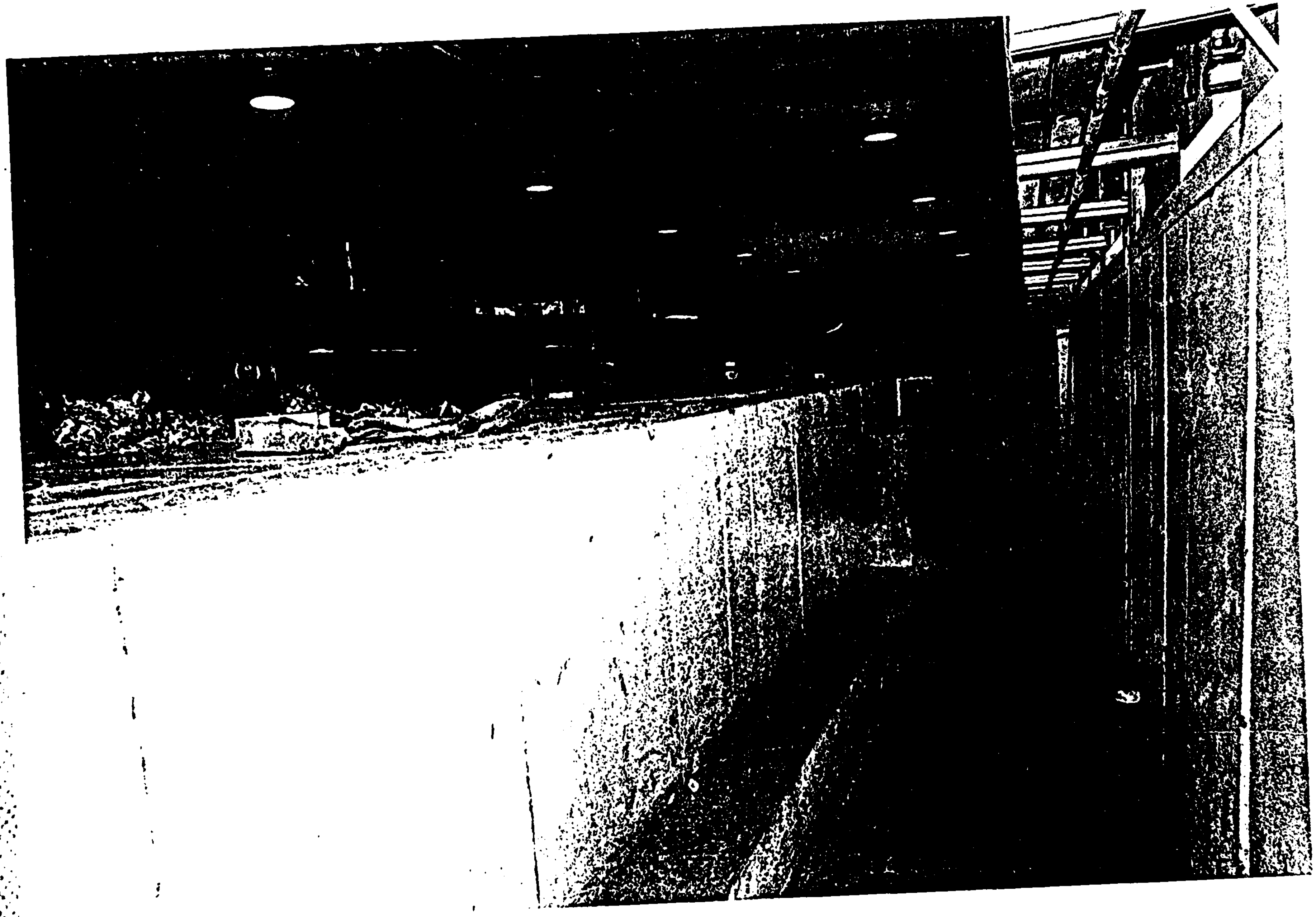

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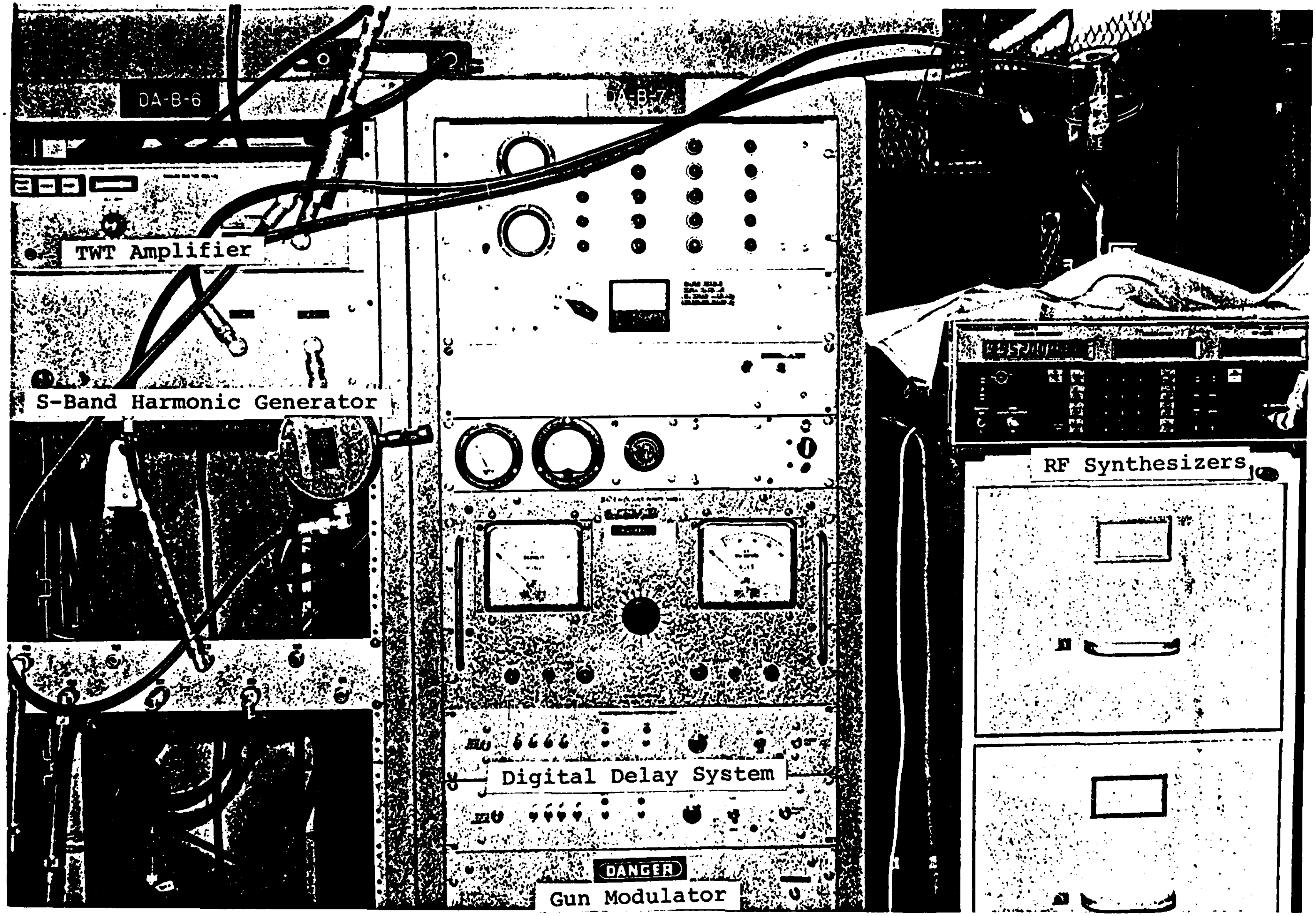
DA-B-6
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RF Synthesizers
Digital Delay System
DANGER
Gun Modulator

Figure 4

Figure 5

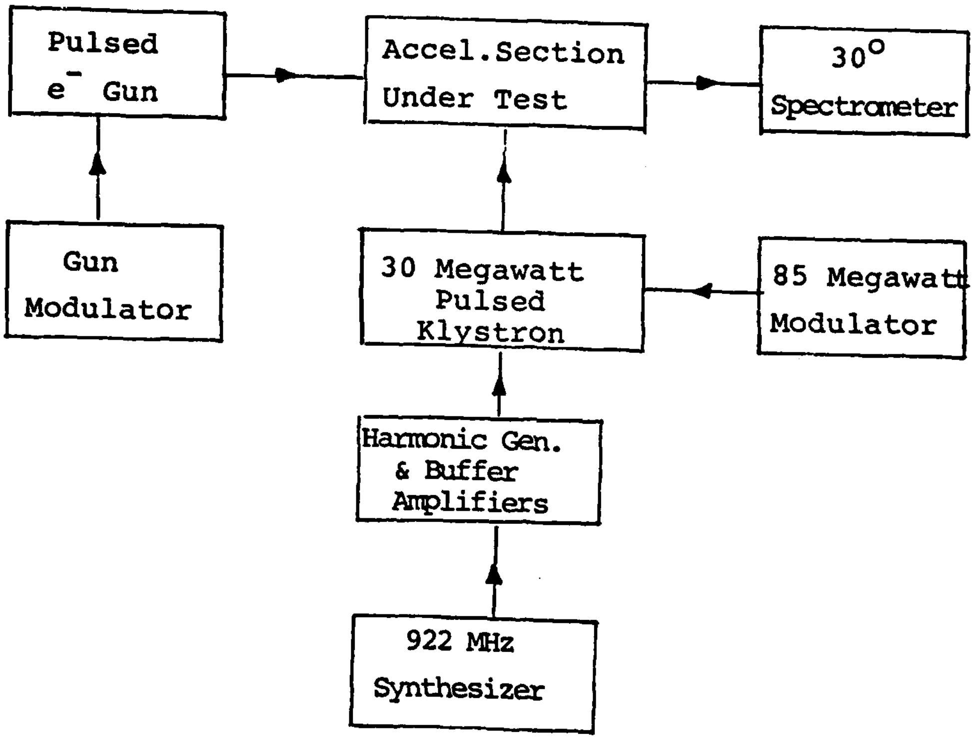
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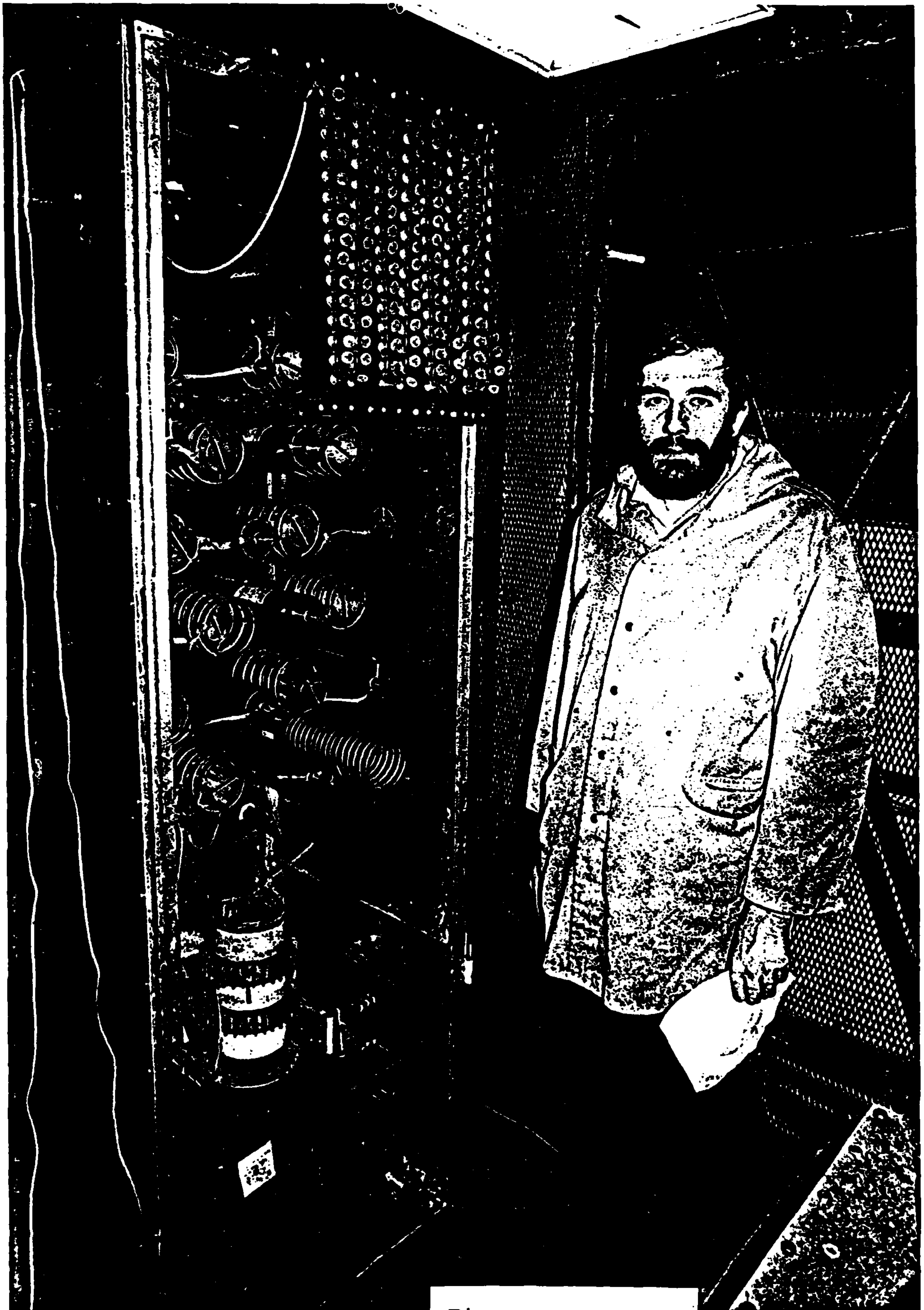
Figure 6



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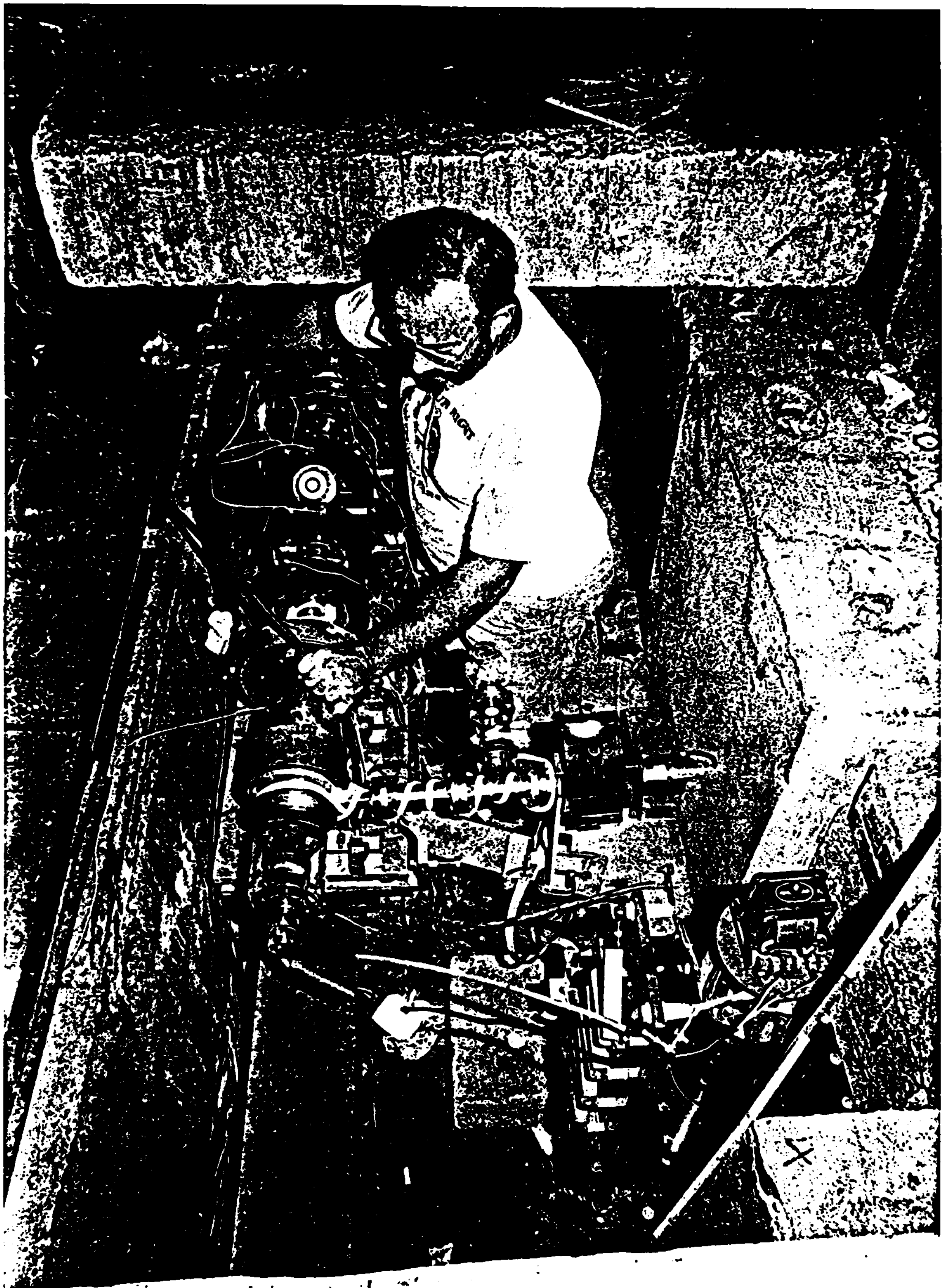

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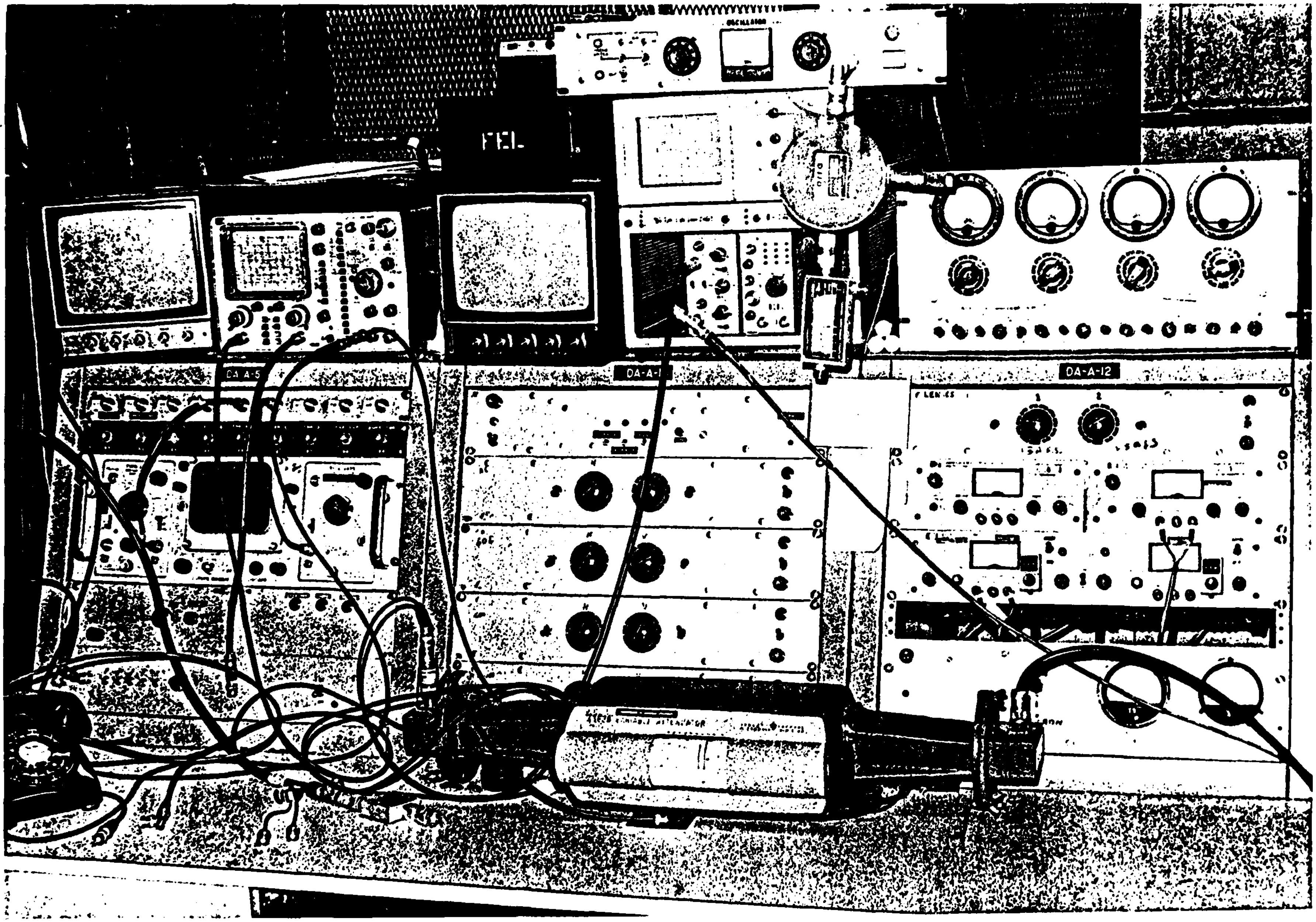

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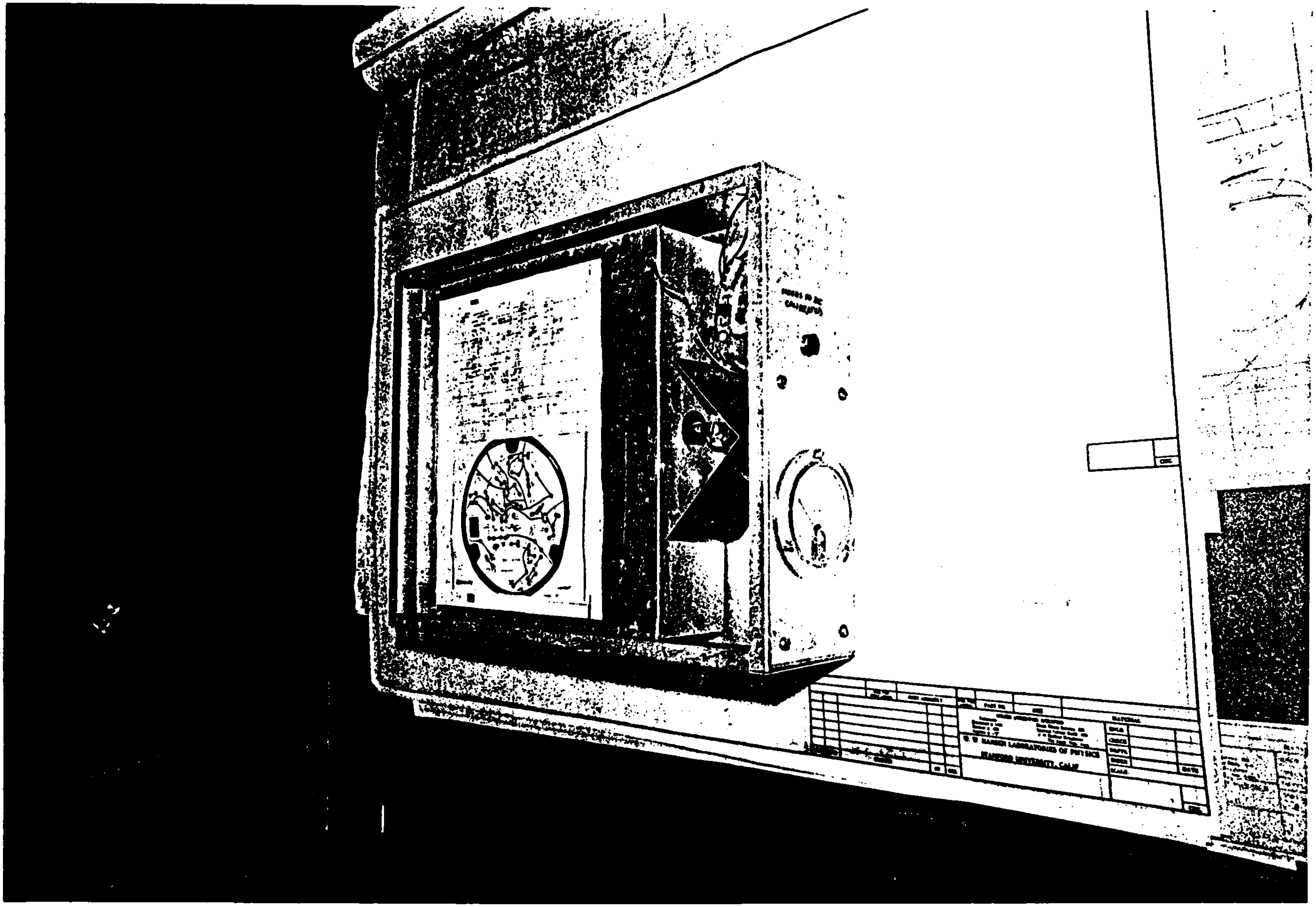

Figure 10

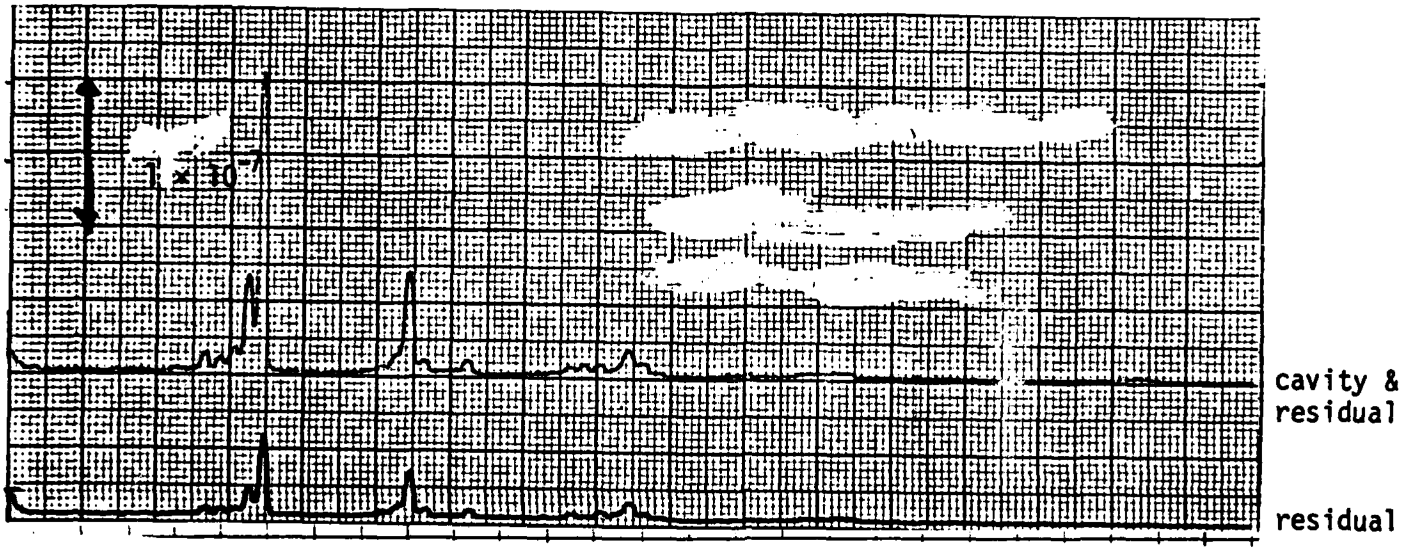

Figure 11

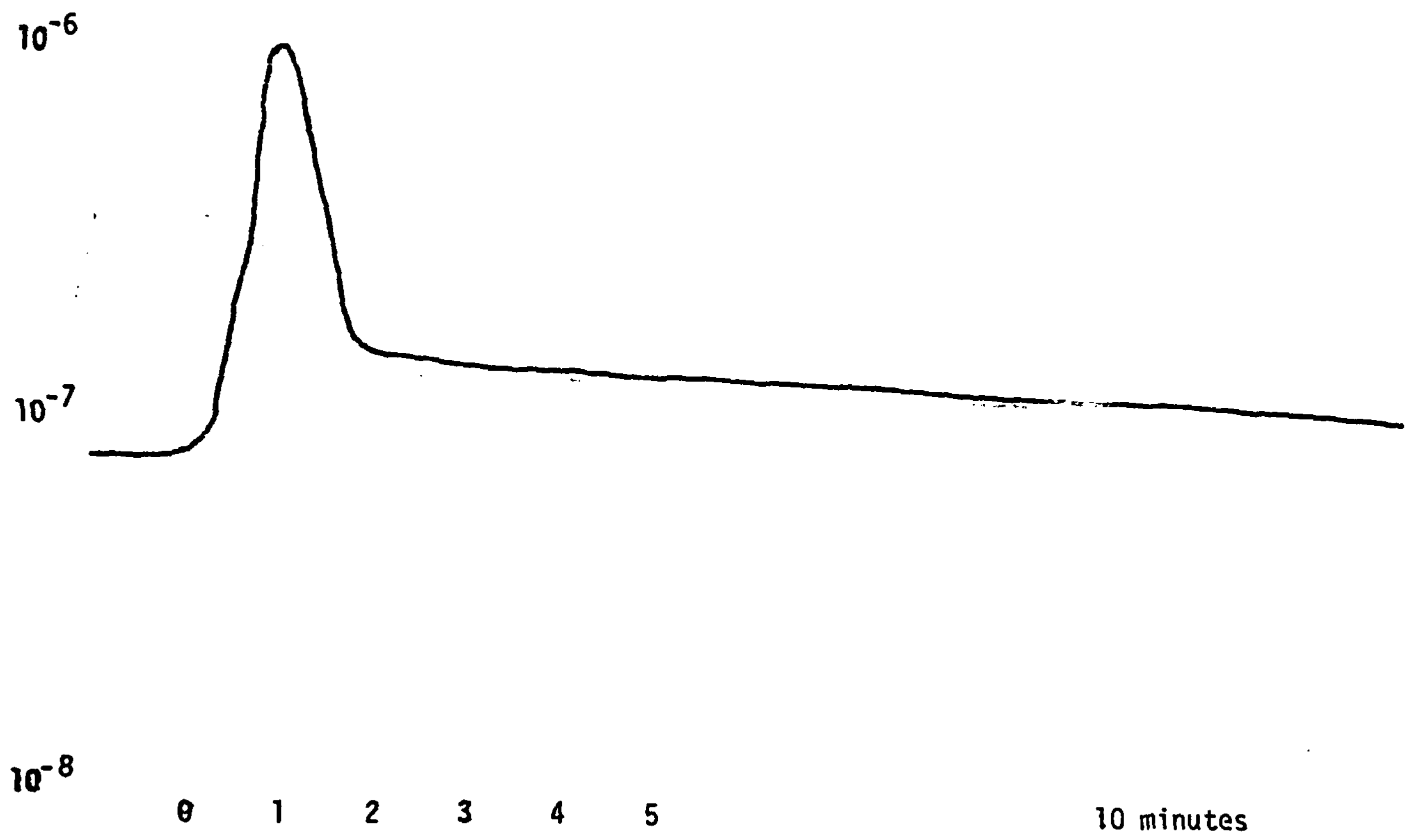

Figure 12

Spectrometer Signal

Figure 13